

Sample-specific and Ensemble-averaged Magnetoconductance of Individual Single-Wall Carbon Nanotubes

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We discuss magnetotransport measurements on individual single-wall carbon nanotubes (SWNTs) with low contact resistance, performed as a function of temperature and gate voltage. We find that the application of a magnetic field perpendicular to the tube axis results in a large magnetoconductance of the order of e^2/h at low temperature. We demonstrate that this magnetoconductance consists of a sample-specific and of an ensemble-averaged contribution, both of which decrease with increasing temperature. The observed behavior resembles very closely the behavior of more conventional multi-channel mesoscopic wires, exhibiting universal conductance fluctuations and weak localization. A theoretical analysis of our experiments will enable to reach a deeper understanding of phase-coherent one-dimensional electronic motion in SWNTs

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The study of magnetotransport is a powerful tool for the investigation of the electronic properties of mesoscopic systems [1]. In single-wall carbon nanotubes (SWNTs), however, only limited magnetotransport studies have been performed until now. These studies have mainly focused on effects originating from the coupling of the magnetic field to the electron spin [2, 3, 4, 5], whereas effects originating from coupling to the orbital motion have not received much attention until very recently [6, 7]. This is probably because the lateral dimensions of SWNTs are very small, which may have led to the idea that orbital effects could play a relevant role only in the presence of an extremely high magnetic field, beyond experimental reach [8].

Many basic questions regarding the magnetoconductance of SWNTs have so far been left unanswered by the lack of systematic experimental investigations. For instance, it is not known what kind of magnetoconductive response would be observed even in simple experimental configurations, such as a metallic SWNTs in the presence of magnetic field applied normally to the tube axis. More specifically, it is not known what determines the magnetic field scale required to induce an appreciable change in an individual SWNT conductance, how large this change would be, and what is the dominant microscopic mechanism responsible for its occurrence. These questions are particularly relevant because SWNTs are considered to be truly one-dimensional conductors in which electron-electron interactions are expected to play a key role [9], with considerable experimental evidence for Luttinger liquid behavior having been reported during the past few years [10].

In this letter we report systematic experimental investigations of magnetotransport through individual SWNTs, which demonstrate the presence of a large magnetoconductance of orbital origin, appearing already on a rather small field scale. All our experiments were per-

formed on metallic SWNTs with low contact resistance, to prevent the occurrence of Coulomb-blockade at low temperature. In these samples we observe large ($\simeq e^2/h$) aperiodic magnetoconductance fluctuations upon the application of a magnetic field perpendicular to the tube axis, whose shape strongly depends on the gate voltage. By averaging over different magnetoconductance curves measured on the same SWNT at different values of the gate voltage, we show that it is possible to suppress the aperiodic fluctuations and to reveal the presence of a positive magnetoconductance. We further show that the magnitude of the "ensemble-averaged" magnetoconductance and of the aperiodic fluctuations decreases with

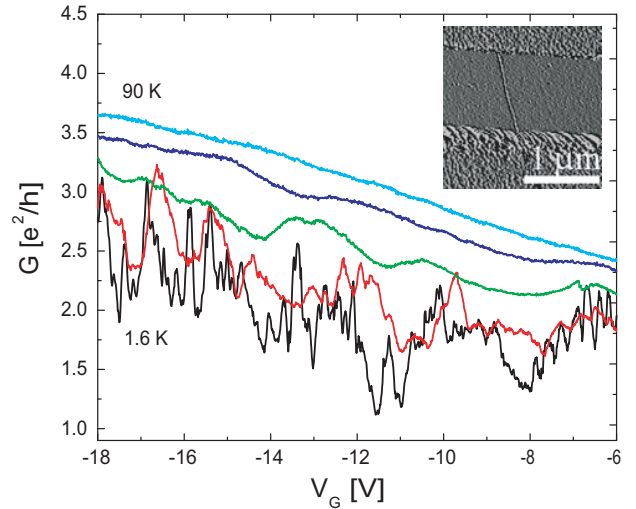


FIG. 1: Gate voltage dependence of the conductance of an individual SWNT (shown in the inset) measured at different temperatures (1.6 K - bottom curve -, 4.2 K, 20 K, 45 K, and 90 K - top curve). Note the aperiodic conductance fluctuations whose amplitude decreases with increasing temperature.

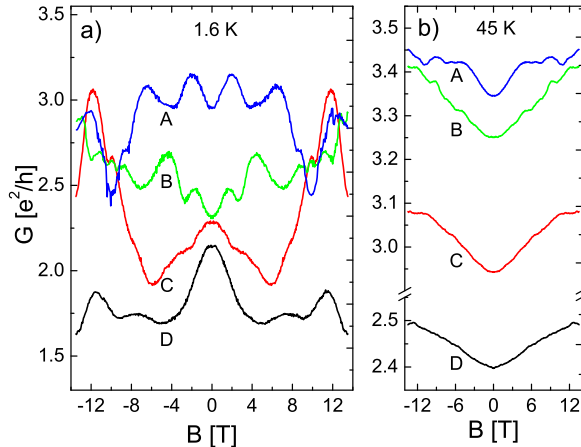


FIG. 2: a) Individual magnetoconductance traces measured at 1.6 K, for different values of the gate voltage (A, $V_G = -16.8$ V; B, $V_G = -15$ V; C, $V_G = -12$ V; D, $V_G = -6.8$ V), showing large aperiodic fluctuations, whose precise shape strongly depends on V_G . Note that both a maximum and a minimum is observed around $B = 0$. b) Magnetoconductance traces measured at $T = 45$ K, for the same values of V_G : at higher temperature, the magnetoconductance has always a minimum around $B = 0$.

increasing temperature. The qualitative behavior of the observed magnetoconductance is interpreted in terms of orbital coupling of the magnetic field, which affects the quantum interference of electron waves in the SWNTs, resulting in magneto-induced conductance fluctuations and in the suppression of weak localization. Our results call for a theoretical analysis of these phenomena, whose occurrence in SWNTs had not been anticipated, which will enable the quantitative determination of the yet unknown phase-coherence time in SWNTs and will deepen our understanding of the interplay between quantum interference and electron-electron interaction in these systems.

The devices used in our investigations consist of an individual metallic SWNT in between two contacts, prepared on a degenerately doped silicon substrate (also acting as gate electrode) coated with a 500 nm-thick thermally grown oxide layer. The SWNTs are deposited by means of a chemical vapor deposition process [11]; the electrodes consist of a Pd layer (10 nm thick) covered with a second $\text{Au}_{0.6}\text{Pd}_{0.4}$ layer (15 nm thick), resulting in a high yield of samples having a contact resistance lower than the quantum resistance [12]. The overall details of the fabrication process are very similar to those described in Ref. [13]. Magnetotransport measurements were performed on different devices which show identical qualitative behavior. Here we will discuss data obtained from one single sample, representative of this behavior.

Figure 1 shows the conductance G of an individual

SWNT measured as a function of gate voltage V_G , at different temperatures. With varying V_G , the conductance exhibits pronounced aperiodic oscillations whose peak-to-peak amplitude is $\delta G \simeq e^2/h$ at 1.6 K and decreases with increasing temperature. This behavior is commonly observed when measuring low-temperature transport through SWNTs, with highly transparent contacts. The aperiodic oscillations are attributed to phase-coherent electron waves interfering randomly in the presence of disorder [14]. Whereas transport through disorder-free SWNTs with transparent contacts has been investigated in some detail (e.g., analysis of a Fabry-Perot interference pattern [15]), no systematic study addressing the influence of disorder has been reported to date.

Figure 2(a) shows the magnetoconductance of the same individual SWNT for which the $G(V_G)$ curves are plotted in Fig. 1. The data were taken at 1.6 K with the magnetic field applied perpendicular to the tube axis, for different values of gate voltage. It is apparent that for all values of gate voltage the magnetic field induces large changes in the conductance, the details of which are strongly dependent on the value of V_G . The change in V_G needed to substantially change the measured magnetoconductance (MC) curve is approximately 0.3 V, which corresponds well to the correlation voltage of the $G(V_G)$ curve measured at $B = 0$ (Fig. 1).

For all values of gate voltage, the MC curves are symmetric, as expected for measurements performed in a two-terminal configuration in the presence of time-reversal symmetry [1] and, at 1.6 K, either a maximum or a minimum in the MC is observed around $B = 0$ depending on the value of V_G . The peak-to-peak amplitude of the magnetic field-induced conductance fluctuations is $\delta G \simeq 0.5 e^2/h$, comparable to the fluctuations induced by changes in the gate voltage. The characteristic magnetic field scale of the aperiodic fluctuations is $\delta B \simeq 3 - 4$ T.

As the temperature is increased, the magnitude of the magnetic field-induced conductance fluctuations decreases, similarly to what happens to the gate voltage-induced fluctuations (see Fig. 3). In addition, at higher temperature ($T > 40$ K) the MC exhibits a qualitatively different behavior. Specifically, at sufficiently low field the MC is positive for all values of gate voltage, so that a conductance minimum is always observed around $B = 0$ T as is shown in Fig. 2(b).

The observed conductance fluctuations, which are induced by a change in gate voltage or in magnetic field and have an amplitude close to $\delta G \simeq e^2/h$, resemble very closely universal conductance fluctuations (UCF) seen in multi-channel mesoscopic wires [1]. In these wires, the low-temperature MC originates from the magnetic flux piercing the system, which affects the phase-coherent propagation of electrons in a disordered medium through random Aharonov-Bohm phases acquired by the

electronic waves. The characteristic magnetic field scale for these fluctuations is given by $\delta B \approx \Phi_0/S$, where $\Phi_0 = h/e$ and S is the area of the samples where the phase-coherent propagation of electronic waves takes place. In our sample, this condition corresponds to a value of $\delta B \approx \Phi_0/Ld \simeq 3$ T, which is in good agreement with our experimental findings (here $L \simeq 1 \mu\text{m}$ and $d = 1.5$ nm are the tube length and diameter respectively).

An interpretation of the MC fluctuations in terms of random interference of electronic waves, similar to UCF, also provides a natural explanation for the temperature dependence observed in our experiments. The magnitude of the aperiodic fluctuation decreases with increasing temperature because of two mechanisms. First, the increase in thermal energy results in the population of a broader window of states around the Fermi energy. Second, at sufficiently high temperature the phase-coherence length l_ϕ becomes smaller than the length of the SWNT, so that the tube behaves as a collection of L/l_ϕ independent phase-coherent segments. Both these mechanisms result in the averaging of the random conductance oscillations, causing their suppression.

In conventional mesoscopic conductors, UCF are always accompanied by weak localization and it is interesting to see whether the effect of weak localization on the MC of SWNTs can also be observed experimentally. In a fully phase-coherent conductor, UCF and weak localization have comparable magnitude, which makes it difficult to separate the two phenomena in a single MC measurement. However, upon ensemble averaging, random MC fluctuations can be suppressed whereas weak

localization (WL) remains unaffected [16].

For this reason, we have performed an ensemble average of the MC of an individual SWNT using as ensemble $N = 34$ MC traces measured at different values of V_G in the interval -6 V to -18 V. This procedure is motivated by the analogy with conventional mesoscopic wires, for which it has been theoretically proven that a sufficiently large change in Fermi energy (induced in our case by the gate voltage) is equivalent to a complete change in impurity configuration, in so far as the conductance oscillations are concerned [17]. In the experiment, the separation in V_G between adjacent MC traces is 0.3 V, corresponding approximately to the position of the half-width in the autocorrelation function of $G(V_G)$.

The result of the ensemble average is shown in Fig. 4(a). It is apparent that the ensemble-averaged MC is always positive, as it is expected if WL is mechanism for the presence of MC. The magnitude of this positive MC decreases gradually with increasing temperature, which is consistent with the phase-coherence length in the nanotube becoming shorter -also as expected- with increasing T . That there is essentially no difference between the ensemble-averaged MC measured at 1.6 K and 4.2 K, indicates that in this temperature range l_ϕ is longer than the length of the SWNT. Note also that at 1.6 K and 4.2 K some structure is still visible superimposed on the background of the positive MC, because the averaging procedure only suppresses the magnitude of sample-specific fluctuations by a factor of \sqrt{N} (approximately equal to 6 in our case). This structure is less pronounced at higher temperature, when thermal effects and a phase-coherence length shorter than the tube length also contribute to averaging remnant sample-specific features.

Having understood the phenomena responsible for the observed MC, we try to quantify their magnitude more accurately. The magnitude δG_{CF} of the aperiodic conductance fluctuations (CF) is quantified in terms of their rms value. This, we directly calculate from the individual $G(B)$ traces after subtracting the averaged magnetoconductance curve $\langle G(B) \rangle$, to remove the effect of weak localization. Fig. 4b shows the resulting temperature dependence of δG_{CF} (note that, at each temperature, we have also averaged the values of δG_{CF} obtained at different values of V_G to improve the statistical accuracy of our result). An estimate of the amplitude of weak-localization correction to the conductance δG_{WL} is less straightforward at this stage. Here, we simply take $\delta G_{WL} = \langle G(14 \text{ T}) \rangle - \langle G(0 \text{ T}) \rangle$ (also plotted in Fig. 4(b) as a function of temperature). However, we emphasize that this value of δG_{WL} is not accurate, both because 14 T (the largest field reachable in our measurement set-up) may not be sufficient to fully suppress weak localization and because remnant structure due to the aperiodic fluctuations is still present in the average MC curve. More accurate measurements of δG_{WL} require the ability to ap-

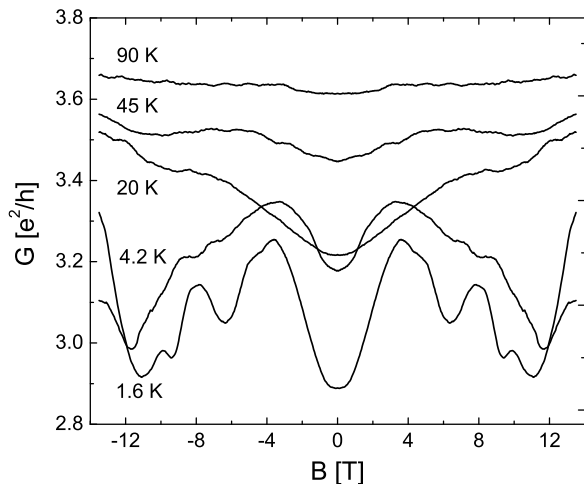


FIG. 3: Magnetoconductance curves measured at $V_G = -17.7$ V for different temperatures, showing that the magnitude of the aperiodic conductance fluctuations decreases with increasing temperature.

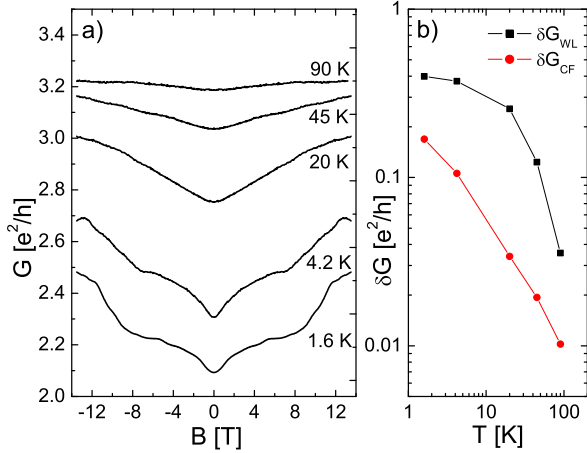


FIG. 4: a) Ensemble-averaged magnetoconductance curves measured at different temperatures. In all cases the average is taken over 34 magnetoconductance traces measured at different values of V_G . It is apparent that a positive magnetoconductance remains after averaging. b) amplitude of the aperiodic conductance fluctuations and of the weak-localization signal as a function of temperature. The lines are a guide to the eye.

ply a higher magnetic field and the use of a larger number of MC curves in the calculation of the ensemble-averaged magnetoconductance.

These results give a fully quantitative answer to the questions that have been posed earlier. A large orbital magnetoconductance is visible in metallic SWNTs already at low magnetic field, due to the quantum interference of electron waves. The magnetoconductance is large even though the electronic motion is nearly ballistic, as indicated by the average transmission per channel which reaches values as high as $\simeq 0.9$ (in Fig. 1 the conductance reaches values larger than $3.5 e^2/h$). This shows that imperfections in the SWNTs that cause only a minor amount of backscattering can affect electronic interference strongly. Specifically, even small imperfections can prevent the observation of a regular Fabry-Perot interference pattern and result in a random pattern of conductance oscillations (both as a function of gate voltage and of magnetic field).

In spite of the fact that the observed phenomenology is very similar to that of mesoscopic conductors of higher dimensionality [18], there exist no theoretical description of UCF and WL in SWNTs enabling a quantitative analysis of our results. Note that in this regard that the situation in SWNTs differs from that of multi-walled nanotubes (MWNTs), where UCF and WL can be described satisfactorily in terms of the conventional theory for quasi-1D diffusive conductors [19]. For MWNTs this works probably because the mean free path is comparable or shorter than the tube circumference, which justifies the

hypothesis of diffusive motion. In addition, the geometrical dimensions of MWNTs are considerably larger than the Fermi wavelength, which is a necessary condition for the validity of the conventional theory based on a semiclassical approximation.

Both these conditions are not fulfilled in SWNTs, and the theoretical analysis of WL and UCF will have to be based on a different starting point. We believe that in SWNTs the presence of two bands at the Fermi energy is particularly important to account for the magnetoresistance observed here. This is because with two degenerate sub-bands even a small magnetic field can induce subband mixing and change the scattering matrix (and thus the conductance) of a SWNT sample. This mixing would of course not be possible if SWNTs would have only one conduction channel (as one may naively assume, since SWNTs are often referred to as an "ideal" realization of 1D conductor), in which case we expect that UCF and WL would be absent. Finally, theory will have to consider that in SWNTs electron-electron interaction plays an important role, and may require a Luttinger liquid description of the electron system. This makes the analysis of WL and UCF in SWNTs particularly interesting, since so far the theoretical analysis of these phenomena has been confined to the case of Fermi liquids. In this regard, we also emphasize that the analysis of our data in terms of a fully quantitative theory should enable the determination of the phase-coherence time and its temperature dependence in SWNTs, which is currently unknown.

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